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A new device for determining the compression after impact strength in thin laminates

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Abstract: In this work a new device has been developed to estimate compression-after-impact (CAI) strength. This device allows the testing of laminates thinner than those recommended by CAI test standards. The pro-posed device is composed of a support structure, with a set of vertical ribs that stabilize the specimen during the test, increasing the buckling load. A numerical analysis was made to ensure that global buck-ling does not occur in the laminate during the CAI test, and that there is no interference with the damage area. Laminate specimens were tested with the proposed device and the ASTM device. For specimens 4.416 mm thick (thickness according to ASTM D7137 standard), the test results were similar with both devices. For thinner laminates, higher CAI strength was estimated with the proposed device than with the ASTM device, showing that the global buckling was delayed.

Keywords: Compression after impact, Thin laminates, Composites, Residual strength.

1. Introduction

Composite laminates are particularly sensitive to low-velocity impacts due to low out-of-plane strength. No clear definition of a low-velocity impact is available, nor is a distinction between high- or low-velocity impact. Usually, if the duration of the impact is long enough so that the response of the structure plays a role, the impact is considered to be low velocity. In this case, the beha-viour of the laminate is highly influenced by the boundary condi-tions [1]. Impact damage begins by the matrix cracking, which generates delamination at the interfaces between layers with dif-ferent fibre orientations, and this could eventually lead to fibre fail-ure [2]. Fibre failure (intra-laminar damage) affects mainly tensile strength, while delamination (inter-laminar damage) decreases mainly compression strength.

A low-velocity impact on a composite structure can cause inter-laminar damage that diminishes the residual strength. This type of impact is especially dangerous because of its difficult detectability. Therefore, low-velocity-impact tests should be performed on composite structures, and subsequently damage progression should be evaluated under different load conditions, to determine the residual strength value of the component. The compression-after-impact (CAI) test is of great interest within the aeronautical industry, since the residual compressive strength of the damaged component is the property that decreases the most.

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In a CAI test, a compressive load is applied to a damaged laminate. As the applied load becomes greater, local buckling occurs, generating out-of-plane stresses around the delaminated area [3]. When the load increases, more out-of-plane stresses appear around the delaminated area. The post-buckling continues until out-of-plane stress exceeds the critical strain-energy-release mode I value or interlaminar strength. Final failure occurs because the delamination propagates perpendicularly to the applied load, and the laminate collapses [4].

Composite structure design requires knowing the CAI strength of the laminates comprising it. The CAI strength is not a material property, since it is strongly influenced by the geometry of the impacted structure, support conditions, and the characteristics of the impactor. To measure this strength a uniaxial compression test is made on an impacted plate specimen. This test could be carried out according to several standards [5–9], such as ASTM D7137 "Standard Test Method for Compressive Residual Strength Properties of Damaged Polymer Matrix Composite Plates" [5].

All of these standards use a symmetrical and balanced laminate specimen, in which the side edges are supported and the upper and lower edges are fixed. ASTM defines the specimen geometry and characteristics of pre-impact test. Currently, this CAI test methodology [5] employs a laminate thickness greater than 4 mm. When samples of less than 4 mm thick are tested using existing standards, global buckling occurs. However, most laminates from the aerospace industry are very thin. The typical thickness of laminates in the horizontal tail plane, vertical tail plane, and fuselage are between 2 mm and 6 mm, and even zones of these primary structures may be less than 2 mm thick. Also, for control surfaces, laminates can be 1–3 mm thick. Thin laminates require an alternative method to estimate this property in order to prevent global buckling prior to the damage spread caused by an impact. Some authors have employed the method of the ASTM standard to analyse the buckling of thin laminates damaged by impact [10], although global buckling occurred during the compression test of all specimens, both impacted and unimpacted.

The scientific literature offers several proposals for the CAI test of thin specimens [11–17]. Some researchers [11,12] have used devices with anti-buckling supports similar to ASTM device, to test thinner and smaller specimens.

Sjöblom and Hwang [13] proposed the use of a steel anti-buckling support with a central hole so as not to interfere with the damage, but the use of strain gauges is not possible. Also, this device needs narrow specimens with end tabs, which could mean a change in their geometry after the impact test, and thus additional damage can be generated during the cutting process [18].

Sanchez-Saez et al. [14] proposed a CAI device that stabilizes the specimen by four anti-buckling plates placed on both sides of the specimen. These plates have cut-outs intended not to interfere with the damage. This device, which ensures that the failure will occur in the affected area, has been used to determine the CAI strength of laminates between 1.6 and 2.2 mm and different lay-ups of carbon/epoxy, and low temperature [19]. This device is designed for testing specimens of different dimensions from ASTM, making the comparison of the results more difficult.

The compression device with horizontal rolls from ESWNM department of Airbus Operations SL [15] also increases the critical buckling load to test thinner specimens. This device has lateral guides and rolls to prevent the buckling of the specimen [20]. The method of fixing is by means of screws and, therefore, the specimen edges need not be perfectly parallel for the load applica-tion, but drilling the specimen is needed to fix it to the clamping system. The main disadvantages are that the device allows the testing of only a specific thickness, it does not allow proper place-ment of the strain gauges, and the specimen size is larger than recommended by the ASTM standard, and therefore the compar-ison of the results becomes more difficult.

Other authors use sandwich specimens made by joining a damaged laminate to a core that stabilizes it, and test the ensemble under compression [16,17]. The sandwich structure is much more stable for being thicker, and this would allow the testing of very thin laminates. The problem with this test methodology is the interaction of the damaged area of the laminate with the core of the sandwich, producing failure modes that are not representative of the actual structure. The sandwich stabilizes the sub-laminates created by delamination, delaying its progression, so that there is a risk of finding higher and deceptive residual-strength results.

This paper proposes a new CAI test methodology to test thin laminates, by employing the specimen geometry recommended in the ASTM D7137 standard. The design and validation process of a new device that allows testing laminates under 4 mm thick is described. The proposed device prevents the global buckling in the damaged specimen, ensuring that the failure is due to compression. This approach was experimentally validated, testing quasi-isotropic laminates with three different thicknesses. The results using the developed and the standard devices were compared.

2. Device description

A CAI device was designed, after analysing the damage-progression mechanisms in a CAI test, according to the following requirements:

- The laminate should not reach the critical buckling load, which in a thin laminate is lower than in standard thicknesses.
- The failure does not occur in the load application zone. Crush failure or local buckling should not appear in this zone.
- An accurate alignment between the specimen and the load applied is needed to ensure a state of uniaxial compression stress.
- The device should not interfere with the damaged area, allowing the local buckling of sub-laminates and the progression of the delamination.
- The friction should not be a source of uncertainty in the results.
- It should be possible to place strain gauges to check the validity of the test.

In addition to the above features, other relevant aspects can improve issues such as manageability or time savings: the device weight, ease of use and installation, visibility of the test, safety of use, device robustness, and ease of industrialization.

In the proposed device, specimen stability was improved by a support structure, with a set of vertical ribs that increase the buckling load. Global buckling of the test specimen must be greater than the local buckling of delaminated sub-laminate or the compressive failure load. In the modelling the laminate, in simplified form, as an isotropic and homogeneous material, the critical buckling stress σ_{crit} can be estimated by Eq. (1) [21]:

$$\sigma_{crit} = K \cdot E_{eq} \cdot \left(\frac{t}{b}\right) \quad (1)$$

where E_{eq} is the equivalent Young's modulus of the laminate in the load direction, b is the buckling distance, which corresponds to the width between supports, and K is a constant that depends on the boundary conditions, the geometry, and the material.

Therefore, to increase the specimen critical buckling load, the buckling distance b (Eq. (1)) should be reduced (Fig. 1). For this purpose, a device with vertical intermediate elements was proposed (Fig. 2).

The device was designed for testing specimens having the same geometry of the specimens used in the ASTM standard (i.e. 100 mm $\times$ 150 mm) and a wide range of thicknesses.

A numerical simulation in Abaqus Standard [22] was performed in order to define the position of the vertical elements. Two-dimensional models were formulated using the module "Linear Perturbation, Buckle" to estimate the critical buckling load of the laminate. Two laminate plates, one subjected to the bound-ary conditions as proposed by the CAI ASTM standard and another considering the existence of intermediate vertical ribs, were simulated.

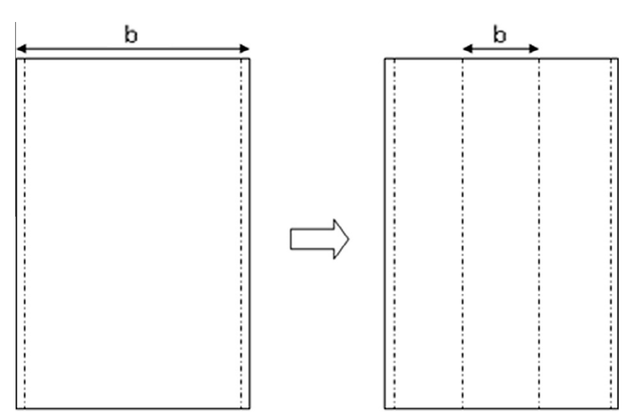

Fig. 1. Reduction of buckling distance in the specimen by intermediate supports.

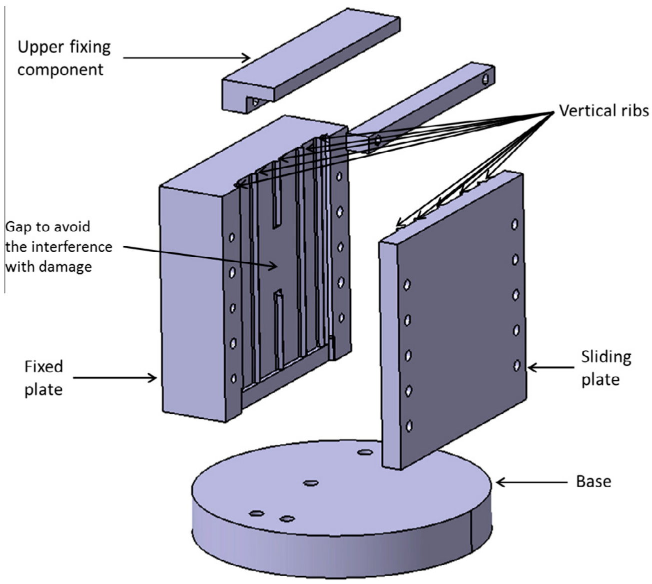

Fig. 2. Description of the proposed device, with vertical intermediate elements to increase the buckling load of the specimen.

Three configurations with AS4/8552 material with a quasi-isotropic lay-up and three different thicknesses were modelled, one with 8 plies [45/0/-45/90]S, one with 16 plies $[45/0/-45/90]_{2S}$, and another with over 24 plies $[45/0/-45/90]_{3S}$, measuring 1.472 mm, 2.944 mm, and 4.416 mm thick, respectively. The mate-rial mechanical properties are shown in Table 1. In the model, the direction 0° coincides with the direction of the load applied. The load applied was simulated as a distributed 100 N/mm load at the top edge. The specimen was modelled with two-dimensional elements. It was mesh with quadrilateral elements with reduced integration (S4R in Abaqus) of 2 mm, using a total of 3750 elements.

Both CAI devices, i.e. ASTM and the proposed one, were modelled introducing boundary conditions for the laminate plate by restricting the displacements or rotations of some nodes (Fig. 3). For the modelling of the ASTM device (Fig. 3a), the displacement in the direction perpendicular to the plane of the laminate $\mathbf{U_3}$ (thickness direction) and the rotations in the top edge were restricted, $\mathbf{UR_1}$ and $\mathbf{UR_2}$. Furthermore, the lateral edges were also supported, the displacements being restricted in the thickness direction, $\mathbf{U_3}$. All movements of the bottom edge were restricted. The proposed device was modelled in the same way (Fig. 3b), but also introducing the restricted displacement in the thickness direction ($\mathbf{U_3}$) due to the vertical ribs.

From the first eigenvalue determined for each laminate, the critical buckling was calculated. Table 2 shows the first eigenvalue (λ) and the critical buckling stress for both devices. It can be seen that the intermediate vertical ribs in the proposed device are useful to delay the buckling, allowing thin laminates to be tested.

For example, the first buckling mode of a laminate 1.472 mm thick is shown in the ASTM device (Fig. 4a), and in the proposed device (Fig. 4b). The first case displays a large area in which out-of-plane displacements associated with global buckling appear, while the second case shows that buckling occurs in the central area between the vertical ribs.

After the simulations, the intermediate vertical ribs in the proposed device were positioned as shown in Fig. 5. As there should be no interference with the impact damage, the central vertical rib has split, leaving a gap, so that the out-of-plane stresses are not restricted, allowing the delamination progression in that area.

Fig. 6 displays the components of the new device, which is composed of two plates, one fixed to the bottom compression platen, and another which can slide perpendicularly to the first one by several fixed pins. Both plates have vertical ribs that face each other. The specimen is placed between the two plates, being supported by all the vertical ribs. Also a fixing component is placed at the upper edge of the specimen. Between the upper element and the plates a gap allows deformation during compression.

The vertical ribs have sharp edges to minimize friction by reducing the contact area. In addition, the top of the vertical ribs are rounded to prevent them from cutting into the specimen (Fig. 6). The proposed device allows strain gauges to be placed between vertical ribs to verify the correct load application and to ensure that no global buckling occurs.

The device was designed to ensure that the failure (local kinking or buckling) does not occur in the top edge of the specimen. Tight tolerances were used to ensure proper alignment of the load.

A patent application PCT/ES2012/070 087 [23] has been submit-ted for the proposed device.

Table 1
AS4/8552 ply properties. Data provided by the manufacturer (Hexcel Composites).

Ply properties	
E_1 (longitudinal Young modulus)	130 GPa
E_2 (transversal Young modulus)	10 GPa
ν_{12} (Poisson ratio)	0.3
G_{12} (in-plane shear modulus)	5 GPa
t (ply thickness)	0.184 mm

3. Mechanical testing

3.1. Material and test specimens

AS4/8552 carbon/epoxy laminates were used in the tests. These laminates were manufactured by automatic tape laying of unidirectional prepreg tape of 300 mm and cured in an autoclave. The fibre volume fraction of the composite was 59%. Laminates with a quasi-isotropic stacking sequence $[45/0/-45/90]_{nS}$ and three thicknesses were studied. The nominal thickness for the laminates analysed were 1.472 mm (n = 1), 2.944 mm (n = 2), and 4.416 mm (n = 3), respectively. Only the latter specimen thickness meets ASTM standard thickness specifications.

A total of 105 specimens were tested at room temperature and pressure. All specimens measured 100 mm × 150 mm and satisfied the tolerances specified by the ASTM standard. An additional 20 specimens were used in order to define the energies that cause barely visible damage (E_{BVID}).

3.2. Impact tests

Impact tests were performed in a drop-weight tower according to the ASTM D7136 [24] standard. The impactor was a hemispherical nose of 15.9 mm with 5.6 kg of mass. Each specimen was impacted on its smoother side, to facilitate the measurement of the indentation depth. Each specimen received a single impact, and the rebound was prevented by an anti-rebound system.

According ASTM D7136 standard, the tests have to be carried out at an energy that causes barely visible impact damage (E_{BVID}). This energy is defined as the energy that generates an indentation depth in the laminate of about 1 mm [8]. Six speci-mens of each thickness were tested at different impact energies in order to calculate the E_{BVID}, between 7.5 and 40 J (Fig. 7). It was observed that the relationship between the depth of the dam-age and the impact energy could be fit to a straight line in the range of energies and thicknesses studied. From this fitting curve, E_{BVID}

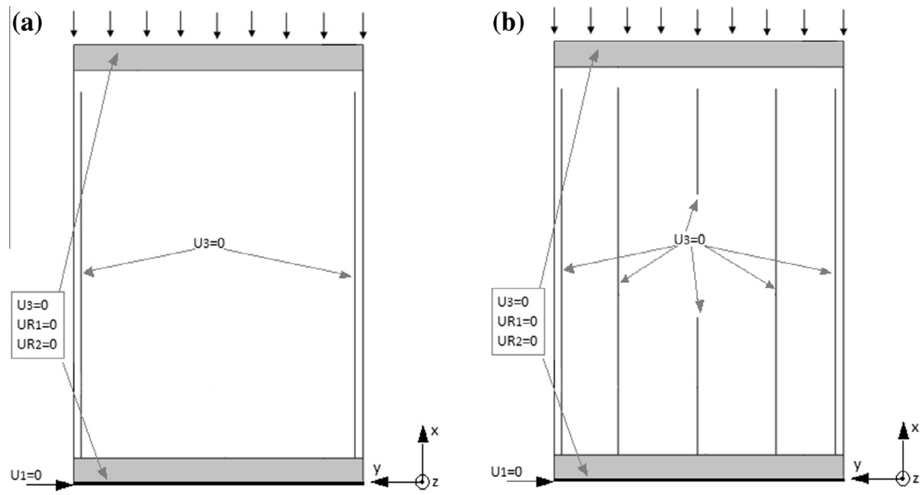

Fig. 3. (a) Boundary conditions of ASTM device, and (b) boundary conditions of the proposed device.

Table 2
First eigenvalue and buckling stress determined for the different cases analysed.

Thickness (mm)	λ		$\sigma_{buckling}$ (MPa)	
	ASTM device	Proposed device	ASTM device	Proposed device
1.472	1.016	4.086	69	278
2.944	8.355	29.001	284	985
4.416	26.781	79.447	606	1799

could be defined for each thickness. For thin laminates, the fitting proved less accurate, having greater scatter in the results of the impact tests because the indentation depth was close to penetration. The E_{BVID} determined were: 9 J for specimens with 1.472 mm of thickness, 22 J for samples of 2.944 mm and 34 J in the specimens with thickness recommended by the ASTM standard (4.416 mm).

3.3. CAI test method

CAI tests, using the ASTM and the proposed device, were performed on a universal testing machine, with a precision of 1% in the range load at a speed of 0.5 mm/min under conditions RT/AR (room temperature/as received). In each test, a load–displacement record was kept. The test device was placed between flat compression platens of the testing machine, with care taken to align the vertical axis of the device with the load direction.

At least five specimens for each thickness and device were tested. The specimens had very tight tolerances, parallelism, and perpendicularity of 0.02 mm. Strain gauges were placed on the test specimen in the load direction, locating two gauges on one side and another on the opposite side, in order to measure longitudinal strain and to be able to detect possible global buckling. Data-acquisition equipment recorded the strain. Average strain values on opposite sides of the specimens were taken to calculate the value of the longitudinal strain. From these data and force provided by the testing machine, the stress–strain curve was drawn.

If the strain values measured by the gauges on opposite specimen sides were not equal, the specimens were bending. The fast divergence in these strain values indicated the onset of global buckling. The bending percentage can be calculated by Eq. (2):

$$\text{Bending percentage} = \frac{\varepsilon_1 - \varepsilon_2}{\varepsilon_1 + \varepsilon_2} \cdot 100 \qquad (2)$$

where ε_1 is the strain of the gauge of one side and ε_2 is the strain of the gauge of the opposite side.

This percentage should be kept below 10% [5], since the onset of instability or excessive specimen flexure invalidates the test. The calculated percentage sign indicates the direction of the bending.

4. Discussion and results

4.1. Experimental validation of the proposed device

The CAI test results from the proposed device were compared with those from the ASTM device in order to validate the new device. A total of 64 specimens 4.416 mm thick were tested (thickness recommended by the ASTM standard), 32 with each device. The residual strength of specimens was estimated without impact and impacted at five different energy levels (between 15 and 55 J). Table 3 shows the mean residual strength and standard deviation. The strength dispersion was similar in the specimens tested with both devices, the coefficient of variation being less than 9.5% with the device proposed and 7.5% with the ASTM device.

Fig. 8 presents the residual strength normalized with the compression strength (for undamaged specimens) estimated with the ASTM device. As the impact energy increased, the residual strength decreased. Even with no detectable damage, the decline in residual strength was very notable (over 50%). For the E_{BVID}, the reduction was close to 60%.

As reflected in Fig. 8, the residual strength estimated with both devices for 4.416 mm specimens proved similar for all impact-energy levels studied.

The analysis of strain measurements showed that buckling did not occur in the specimens tested in either device, the failure strain being similar. For the specimens without impact, the failure strain with ASTM device was 9.683×10^{-3}, and 9.222×10^{-3} for the proposed device.

4.2. Thin laminates CAI tests

CAI tests were performed on 17 specimens 1.472 mm thick and 24 specimens 2.944 mm thick in order to analyse the behaviour after the impact of laminates thinner than recommended by the ASTM standard. Six specimens of each thickness were tested without impact with the new device developed and with the ASTM device, determining the compression strength. Fig. 9 gives the

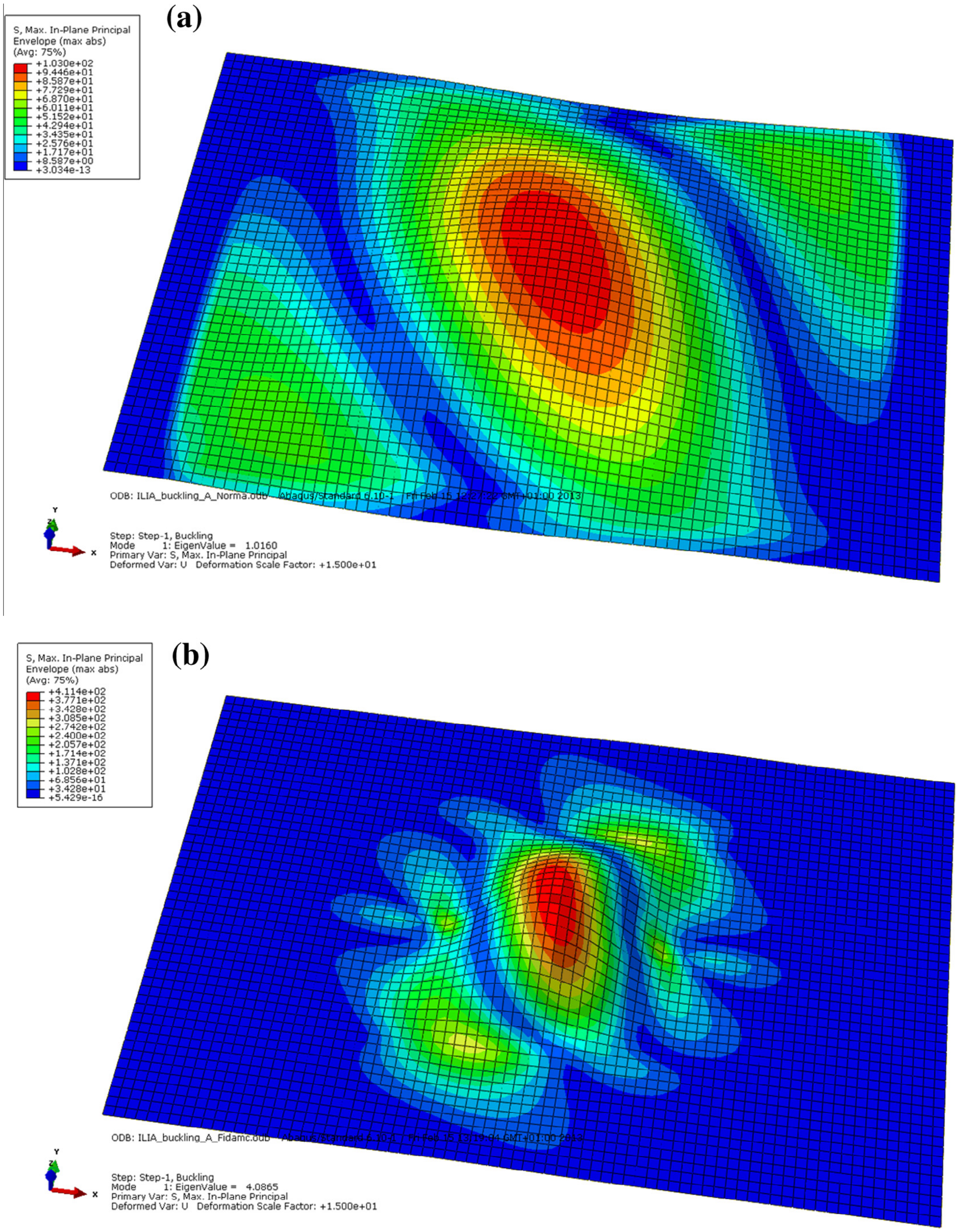

Fig. 4. First buckling mode for 1.472-mm laminate plate simulated in: (a) ASTM device, and (b) proposed device.

mean and standard deviation of the compression strength. The results show a low dispersion (less than 6.8%).

Using the ASTM device, the compression strength for thin laminates (less than 4.416 mm) proved significantly lower than that for specimens of 4.416 mm, 32.0% lower for the thickness of 2.944 mm and 60.3% for the thickness of 1.472 mm. However, for the specimens tested with the proposed device, the strength of specimens of 2.944 mm thickness was found to be similar to that of specimens of 4.416 mm with ASTM device, being 29.9% less for specimens of 1.472 mm thickness. The lower strength in the latter case indicates a certain level of buckling close to failure load, but much less than in the case of using the ASTM device. The decrement of the estimated compression strength for the thin laminates is related to the global buckling of the specimen, the compression strength being higher than the buckling stress (Table 2). A similar result was found for the failure strain (Table 4).

The performance of the thin specimens tested with ASTM device, under both compression strength and failure strain, was due to the global buckling before failure. The global buckling was detected by strain gauges placed on both sides of the specimen. The strain measurements showed a rapid divergence in the thin laminates. As an example, the results of the gauges of the specimens 1.472 mm thick are shown in Fig. 10a. Similar results were found for specimens 2.944 mm thick.

On the contrary, in the thin specimens tested with the device developed, differences between gauge measurements were small.

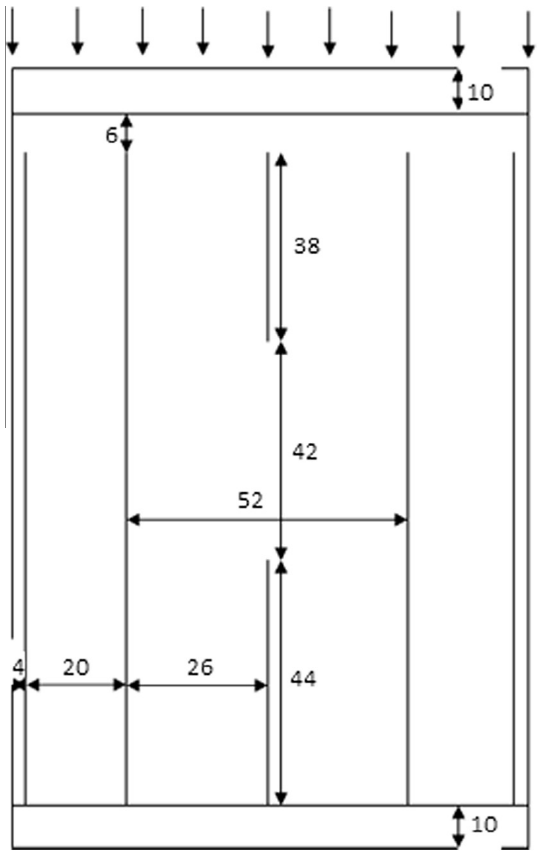

Fig. 5. Position of the vertical ribs on the proposed device (dimensions in mm).

Both gauges were on the same side (G1 and G3) and the facing (G2), and therefore the global buckling was restricted (Fig. 10b). A certain level of global buckling occurred in the proposed device since the gauge measurements differed close to the failure load. The bending percentage with this device was 7.5%, compared to more than 100% with the ASTM device. The results measured with the proposed device are similar to those reported by other authors for laminates 4 mm thick [25]. For specimens 2.944 mm thick, no global buckling was detected in the proposed device.

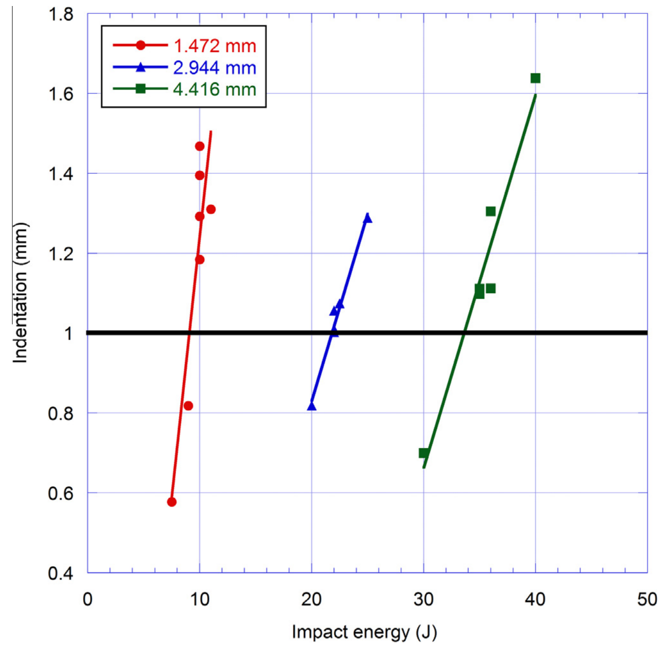

Fig. 7. Indentation depth vs. impact energy for each laminate thickness.

Table 3
Residual strength of the specimens 4.416 mm thick impacted at different energy levels.

Impact energy	CAI strength (MPa)	
	Proposed device	ASTM device
0	402.8±26.9	420.3±0.8
15 J	224.4±5.8	209.0±14.3
25 J	197.4±9.3	177.8±9.9
35 J	191.7±5.8	171.2±4.0
45 J	194.4±6.0	164.2±3.7
55 J	178.0±9.4	149.4±10.9

CAI tests on damaged specimens with an impact energy equal to E_{BVID} were conducted in order to determine the residual-strength variation with the thickness. Since global buckling occurred in the undamaged specimens 1.472 and 2.944 mm thick

Fig. 6. Components of the proposed CAI device and geometry of the vertical ribs.

After the impact test, the specimens were inspected to check the shape of the delamination. An elliptical delaminated area was discerned, the major axis being at about 45°, as expected [2]. After the CAI test, the specimens were inspected again to verify that the delamination progressed in the direction perpendicular to the load direction, ensuring that the failure mode corresponded to compression. In Fig. 11, both the impact damage and its progression perpendicular to the load direction is evidenced for two specimens 1.472 mm thick. At 2.944 mm thick, similar behaviour was found in the specimens.

The residual strength determined when testing thin specimens is shown in Fig. 12. These results were compared with those for specimens 4.416 mm thick.

Although a lower compression strength was observed for the specimens of 1.472 mm thick tested without damage due to global buckling (Fig. 12), in the specimens tested with an impact energy equal to E_{BVID} the CAI strength was similar for all specimen thicknesses. In the 1.472-mm specimens the mean residual strength was 0.5% greater than in the 4.416-mm specimens, and 10.2% in tested with the ASTM device, the CAI tests were performed using only the new device. Six damaged specimens 1.472 mm and 12 of 2.944 mm thick were tested.

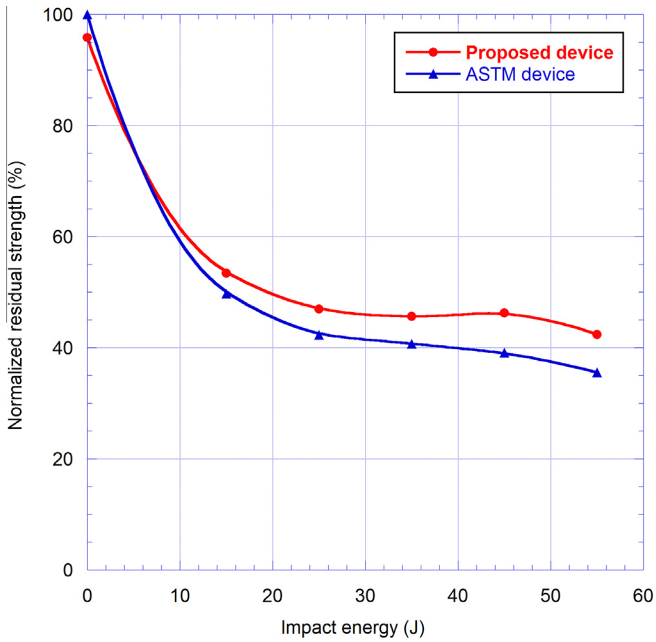

Fig. 8. Normalized residual strength for several impact-energy levels estimated with the proposed device and the ASTM device. Specimen thickness of 4.416 mm.

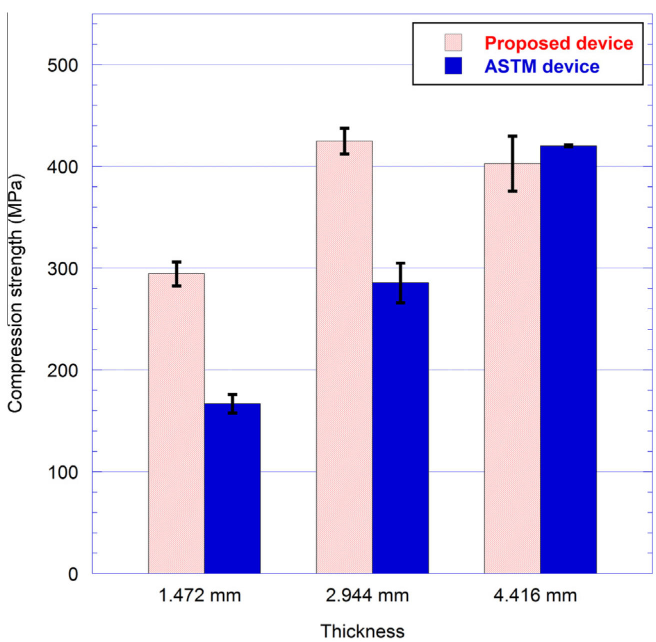

Fig. 9. Compression strength for the specimens of three different thicknesses without impact.

Table 4
Failure strain for specimens of different thicknesses.

	$\varepsilon_{failure}(\mu\varepsilon)$		
	1.472 mm	2.944 mm	4.416 mm
ASTM device	3827	5840	9683
Developed device	7023	9177	9222

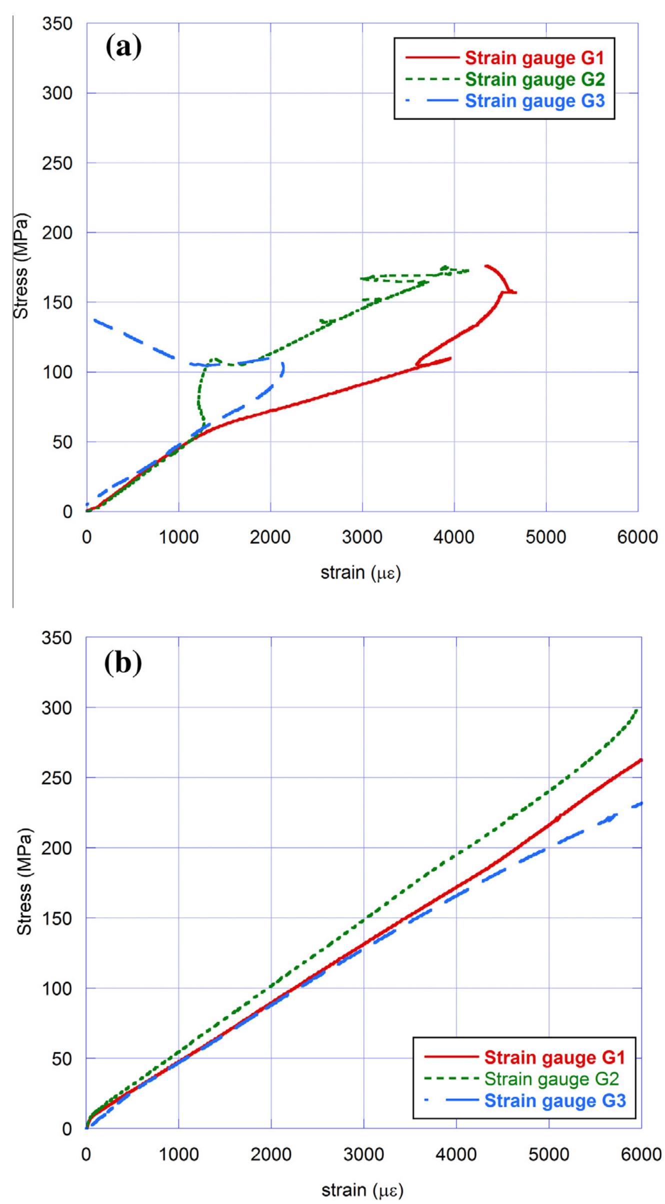

Fig. 10. Stress–strain curves for undamaged specimens 1.472 mm thick: (a) tested with the ASTM device, and (b) tested with the proposed device.

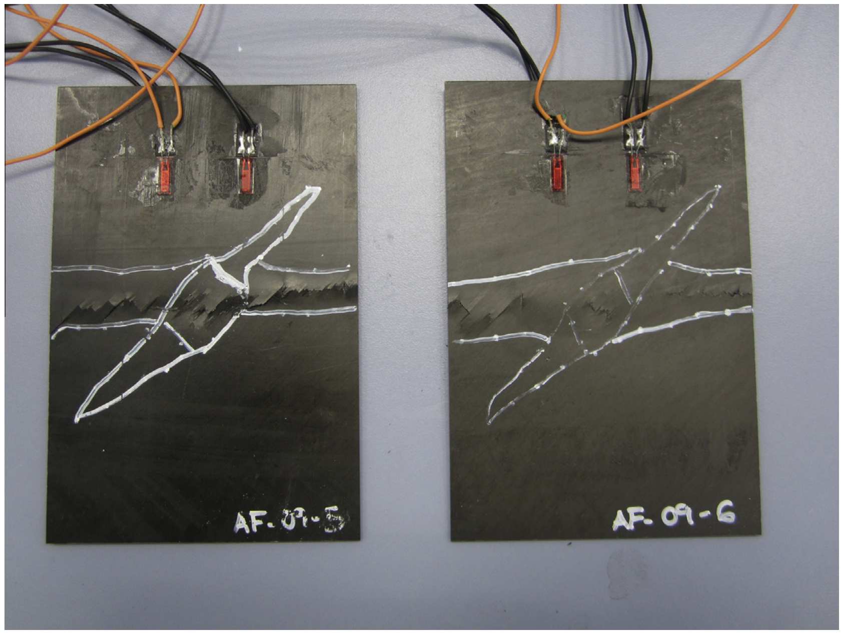

Fig. 11. Specimens 1.472 mm thick impacted at E_{BVID}, inspected after CAI test.

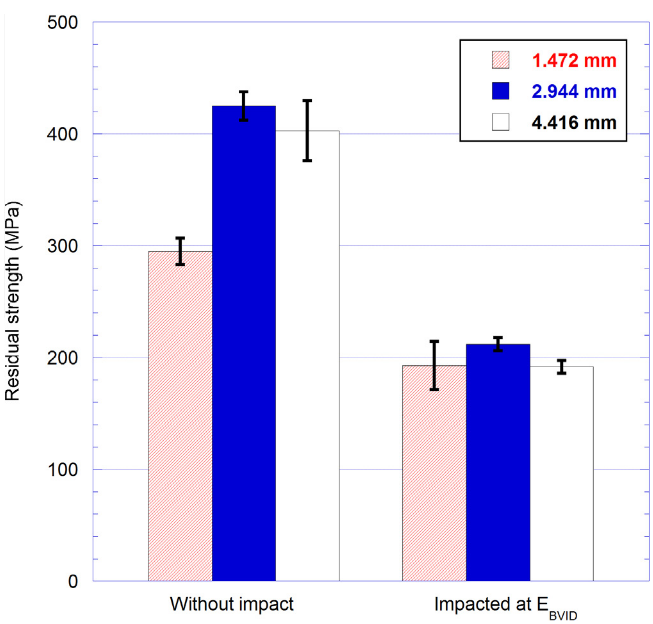

Fig. 12. Residual strength determined with the device developed.

the 2.944-mm specimens. These variations are within the range of experimental scatter (less than 11.2%). In view of these results, it can be concluded that the device developed is a good alternative for CAI testing of thin laminates.

5. Conclusions

Compression after impact test is a relevant topic for the aircraft and aerospace industry, as interlaminar damage is particularly dangerous because of difficult detectability and significant effect on the residual strength of the structure. The number of structural components made of composite laminates with thicknesses less than 4 mm is increasing, but the laminate thickness recommended by CAI standards is greater than 4 mm.

In this work, a new CAI device, which allows thin laminates to be tested, is proposed. A numerical model was used to estimate the global buckling load of different laminate thicknesses tested virtually in the proposed device and ASTM device. The buckling load is higher with the proposed device than with the ASTM device.

The device developed was validated by comparing CAI results of specimens 4.416 mm thick to those found using the ASTM device. Similar CAI strength and failure strain resulted for specimens impacted at several energy levels.

For thin laminates, the compression strength estimated by the ASTM device was lower than the strength of 4.416 mm laminate thickness, being 33% lower for the thickness of 2.944 mm and 63% for the thickness of 1.472 mm. The decreased strength was due to the global buckling of the specimen. This phenomenon was detected by the measurement of strain gauges placed on both sides of the specimens tested. By contrast, the compression strength estimated by the proposed device was similar for specimens 2.944 mm thick and 31% lower for specimens 1.472 mm thick.

The CAI strength estimated by the new device for specimens impacted at EBVID, proved similar in all specimen thicknesses analysed. No global buckling was detected in these tests, and the failure of the laminate was due to compression. Therefore, the proposed device can be used to estimate the CAI strength of thin laminates.

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